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Acceleration of CR at Large Scale Shocks and Their Cosmological Role for Structure Formation in the Universe

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Abstract. We investigate the dynamical importance of a newly recognized possible source of significant feedback generated during structure formation; namely cosmic ray (CR) pressure. We present evidence for the existence of numerous shocks in the hot gas of galaxy clusters (GCs). We employ for the first time an explicit numerical treatment of CR acceleration and transport in hydro simulations of structure formation. According to our results, CRs provide an important fraction of the total pressure inside GCs, up to several tenths. This was true even at high redshift (z=2), meaning that such non-thermal component could affect the evolution of structure formation.

1. Introduction

During the hierarchical process of structure formation, supersonic gas infall and merging events invariably generate powerful, large and long-lived shock waves (Miniati et al. 1999). These should produce copious amounts of CRs, by way of diffusive shock acceleration (e.g. Blandford & Ostriker 1978), including both electrons and ions. In addition, the post-shock gas and diffusively trapped CRs are mostly advected into non-expanding regions, such as filaments and clusters. It turns out that the energy of most of the CR-protons is only marginally affected by radiative losses during a Hubble time. The important possibility, then, is that the latter might accumulate inside forming structures, storing up a substantial fraction of the total pressure there. In addition to cosmic shocks other sources of CRs are also possible. These include AGNs, SNe and stellar winds all of which are candidates for important contributions to the total population of CRs in cosmic structures, although they are not discussed here.

There is growing observational evidence that significant non-thermal activity takes place in GCs. This evidence is provided by extended sources of polarized radio emission, interpreted as synchrotron radiation from relativistic electrons (e.g. Hanisch 1984; Deiss et al. 1997); and by the detection of radiation in excess to what is expected from the hot, thermal X-ray emitting Intra Cluster Medium (ICM), both in the extreme ultra-violet (e.g. Lieu et al. 1996; Kaastra 1998) and in the hard X-ray band above ~ 10 KeV (e.g. Fusco-Femiano et al. 1999; Valinia et al. 1999). Although a coherent picture of the non-thermal status of the ICM is still lacking, a very plausible origin for these radiation excesses is inverse-Compton (IC) due to relativistic electrons (e.g. Sarazin & Lieu 1998). Based on this assumption and on the measured EUV excess in Coma cluster, Lieu et al. (1999) have estimated the existence of a CR proton component in approximate *equipartition* of energy with the thermal gas.

2. Lessons from Hydro Simulations of Structure Formation

Fig. 1a illustrates a slice of a typical cosmic structure formed in a hydro simulation of structure formation with $\Omega_m \equiv \rho_m/\rho_c = 1$, $\sigma_8 = 1.05$, computational box size 32 h^{-1} Mpc and 256^3 cells. It shows contours of compression ($\nabla \cdot v$) corresponding to shock waves, superposed on a grayscale image of X-ray bremsstrahlung emission from the hot ICM (brighter regions correspond to higher emission). We can easily recognize the external, *accretion shock waves* enveloping clusters and filaments and processing for the first time the supersonic (accretion) flows. In addition, however, it is also shown that the ICM of GCs is commonly populated by a complex structure of what we call *internal shock waves*. Unlike the external accretion shocks, internal shocks propagate through gas inside formed (or forming) structures that have already being shock heated. Such shocks include not only *merger shocks* associated with merger events, but also, and more commonly, *flow shocks* that are generated because of the complexity of the supersonic accretion flows. They have similar properties (e.g. size, Mach number) to, but are more common than the largest merger shocks. For this reason they are of primary importance for production of relativistic CRs and must be considered when addressing the issues on the non-thermal activity inside GCs.

Hydro simulations allow us to estimate roughly the expected contribution of cosmic shocks in terms of CR production over cosmological time-scales. The relative importance of the CR dynamical role is usually expressed as the ratio of the CR pressure to the thermal pressure: P_{CR}/P_{th}. The energy stored in CR can be estimated as a fraction $\epsilon_{E_k\to CR}$ of the total kinetic energy that has been processed thorough shocks since a certain epoch, say $z = 1.5$, up to now ($z = 0$). Here, $\epsilon_{E_k\to CR}$ is the conversion efficiency of kinetic energy into CR energy and can conservatively be assumed to be circa 0.1. Then P_{CR}/P_{th} is given by:

$$\frac{P_{CR}}{P_{th}} = \frac{\epsilon_{E_k\to CR}}{2\ E_{th}(z=0)} \int_{t(z=1.5)}^{t(z=0)} (\Phi_{E_k})_{shock} dt \tag{1}$$

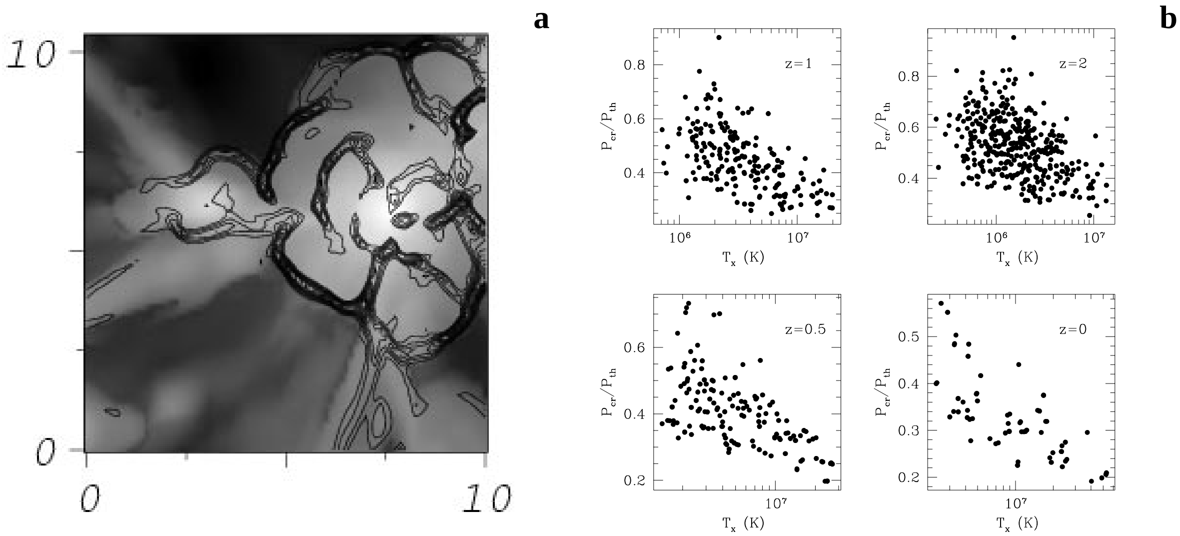

Figure 1. (a) Two dimensional slice of a typical cosmic structure. Scales are in h^{-1}Mpc. (b) Ratio of CR to thermal pressure as a function of GC temperature at four different redshifts.

where P_{th} is the average pressure in the computational box. Here, $(\Phi_{E_k})_{shock}$ is the flux of kinetic energy across shocks. Our conclusions indicate that roughly $P_{CR}/P_{th} \simeq 6 - 8\epsilon_{E_k \to CR} \sim 0.6 - 0.8$ (see Miniati et al. 1999 for more detail). Thus a large fraction of the total pressure inside GCs today could be provided by CRs, in rough agreement with Lieu et al. (1999).

3. Preliminary Results from Explicit CR Numerical Treatment

We have developed unique numerical tools to treat explicitly CR ions acceleration and transport inside simulations of cosmological models (Jones et al. 1999; Ryu et al. 1999). With the CR spatial and spectral information provided by our new scheme, employed in such simulations for the first time, we can assess the question of the non-thermal dynamical contribution in GCs more accurately. In particular, we can begin to explore the ratio P_{CR}/P_{th} as a function of the cluster temperature and for different redshifts. In the simulation described here we have adopted for the fraction of postshock thermal particles to be injected at the shock, the value $f_{inj} \simeq 10^{-4}$. Our results are shown in Fig. 1b. First of all, they indicate that for any T_x and z P_{CR} is *not* a negligible fraction of P_{th}, in accord with our previous findings. Also, the four panels show that for any z the ratio P_{CR}/P_{th} tends to be larger for smaller clusters. Finally, such a ratio not only is still not negligible at high z, but it is actually larger at higher z. This indicates that the evolution of the large scale structure could be significantly affected by this dynamical component.

4. Discussion & Conclusions

We have shown that the ICM of GCs is commonly populated by numerous internal flow shocks with similar characteristic to, but not necessarily associated with major merger events. These along with accretion shocks and merger shocks are likely to play an important role for the non-thermal activity of the ICM. We have also shown that CR pressure could provide a substantial fraction of the total pressure in GCs today, thus affecting GC mass estimates based on the hydrostatic equilibrium assumption and in turn, the baryonic fraction estimates (which end up being biased high). We have also shown that CR pressure was significant already at high z, therefore possibly affecting the evolution of structure formation. Since this is often used as a tools for discriminating among different cosmological models (e.g. Carlberg et al. 1997; Bahcall & Fan 1998), the role of CR pressure should be well understood in order to apply evolutionary arguments with confidence.

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